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The Role of the Engineered Barrier System in Safety Cases for Geological Radioactive Waste Repositories: An NEA Initiative in Co-operation with the EC
Process Issues and Modelling

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Abstract – *The Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee in co-operation with the European Commission (EC) is conducting a project to develop a greater understanding of how to achieve the necessary integration for successful design, construction, testing, modelling, and assessment of engineered barrier systems. The project also seeks to clarify the role that the EBS plays in assuring the overall safety of a repository. A framework for the EBS Project is provided by a series of workshops that allow discussion of the wide range of activities necessary for the design, assessment and optimisation of the EBS, and the integration of this information into the safety case. The topics of this series of workshops have been planned so that the EBS project will work progressively through the main aspects comprising one cycle of the design and optimisation process.*

This paper seeks to communicate key results from the EBS project to a wider audience. The paper focuses on two topics discussed at the workshops: process issues and the role of modelling.

I. INTRODUCTION

The development and implementation of acceptable repository concepts for radioactive waste management may best be approached through an inclusive and open and transparent stepwise decision-making process [1]. A key input to the decision-making process on whether and how to proceed from one stage of waste management to the next is a safety case for the repository.

The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility [2].

Repositories for deep disposal of radioactive waste typically rely on a multi-barrier concept in which several complementary barriers are designed to contain and isolate the waste from the biosphere. The multi-barrier system typically comprises the natural geological barriers provided by the repository host rock and any overlying rock formations, and an engineered barrier system (EBS) that comprises the man-made, engineered materials of the repository.

The "Engineered Barrier System" represents the man-made, engineered materials of a repository, including the waste form, waste canisters, buffer materials, backfill, and seals [3].

II. THE NEA EBS PROJECT

The Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee in co-operation with the European Commission (EC) is conducting a project to develop a greater understanding of how to achieve the necessary integration for successful design, construction, testing, modelling, and assessment of engineered barrier systems. The project also seeks to clarify the role that the EBS plays in assuring the overall safety of a repository [3, 4].

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III. ROLE OF THE EBS

The main functions of EBS components can be summarised as follows [3]:

- The waste form is designed to provide a stable matrix that is resistant to leaching and gives slow rates of radionuclide release for the long-term.
- The container/overpack is designed to facilitate waste handling, emplacement and retrievability, and to provide containment for up to 1,000 years or longer depending on the waste type and disposal concept.
- The buffer/backfill is designed to stabilise the repository excavations and the thermo-hydro-mechanical-chemical conditions, and to provide low permeability and/or diffusivity, and/or long-term retardation of radionuclide migration.
- Seals are designed to prevent releases via tunnels and shafts and to prevent access to the repository.

These functions have been taken into consideration throughout the discussions at the project workshops.

IV. APPROACH TO PERFORMANCE AND SAFETY ASSESSMENT

A systematic approach can help to build confidence in the performance assessment (PA) and safety assessment (SA) models that form part of the safety case. Such an approach may include the following elements:

1. A comprehensive consideration of features events and processes (FEPs).
2. Quantification of uncertainty and variability.
3. Sensitivity analyses.
4. Development of understanding, confidence building and iterative model development.

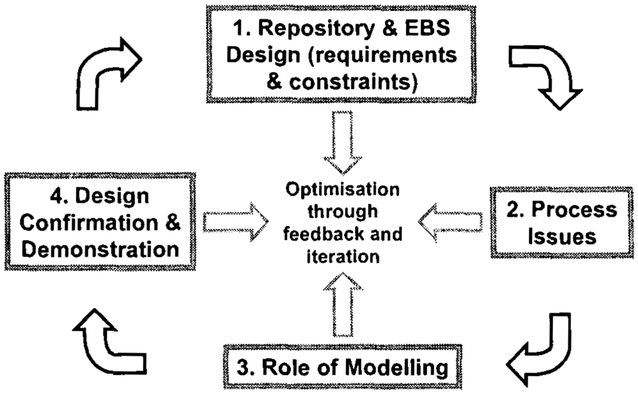

Fig. 1. The EBS Project Optimisation Cycle.

One of the key aims of a systematic FEPs analysis is to provide assurance that the relevant processes have been identified and treated in an appropriate way. It is important that process models and performance and safety assessment models include the potentially significant FEPs, and that the reasons for excluding FEPs from the models are well justified and traceably recorded.

Uncertainty is inherent in all studies. Several types of uncertainty can be distinguished relating to uncertainty in future events and scenarios, in parameter values and the underlying data, and in conceptual models. Further complexity is introduced by spatial heterogeneity and variability in the properties of the wastes, the EBS materials, and the repository host rocks. Information gathering activities should be directed at reducing the most significant uncertainties as far as this is practicable. However, because of variability in the near field and EBS, and limited understanding about how processes will operate in the future; uncertainty cannot be completely eliminated.

Adopting a clear strategy for model development across an entire waste disposal programme and the use of consistent approaches to the treatment of uncertainty can help when comparing models and model results. For example, it is important to know where conservative assumptions or parameter values have been used to take account of uncertainties and bound the effects of particular processes.

Many processes operating within the EBS are complex and/or nonlinear, and many strong process couplings exist. This is particularly the case for high-level waste (HLW) and spent fuel disposal systems where heating effects are coupled to mechanical and hydrogeochemical processes. In such circumstances it can be difficult to identify the most important uncertainties and sensitivities from a simple evaluation of model results. Structured approaches to sensitivity analysis can help to:

- Determine which variables have the greatest impact on the overall uncertainty in model outcomes.

- Examine what happens when the system is stressed via unfavourable parameter values, assumptions, or alternative conceptualisations.

- Identify relevant aspects of individual process models for incorporation into system-wide PAs.

A systematic programme of work will be needed to build confidence in process models and PA/SA models. Building confidence in models is an iterative process that can benefit from the implementation of the steps discussed above as well as iteration between model development, assessments, data collection, and peer review.

V. EBS PROCESS ISSUES

EBS Project Workshop 2 [7] focused on the processes that may influence the performance of the EBS.

V.A. Identifying and Considering Processes

The processes that could occur within an underground repository for radioactive waste are well-known and their significance to each national programme, repository concept and repository site is being assessed. The more advanced programmes have developed and are actively using established approaches for assessing the overall safety of waste disposal and the associated uncertainties. These assessments are also being used in an iterative fashion to refine the design of the repository and arrive at solutions for waste disposal that not only comply with or exceed relevant safety standards, but also ensure that the repository can accommodate the wastes in an efficient and cost effective manner.

Radioactive waste repositories will need to remain operational and receive radioactive waste for a period of the order of 100 years. Increased attention is now being given to assessing the potential effects of the processes that could occur during this long 'pre-closure' period. These 'pre-closure processes' will determine the state of the repository at the time of repository closure. The majority of the 'pre-closure processes' are the same as those that have already been included in assessments of longer-term 'post-closure' repository safety.

However, some FEPs have particular relevance in the earlier part of repository evolution and, owing to recent trends towards longer operating periods and phased repository closure strategies, these FEPs may require greater attention than they have received in previous assessments.

Key questions include:

- How to guarantee the quality and maintenance of EBS materials during the pre-closure phase?

- How to avoid affecting the safety functions of the host rock (e.g. de-saturation) during the pre-closure phase?

- How to minimise stray materials (oil, equipment, metals) during the pre-closure phase?

Other examples of 'pre-closure FEPs' include, drawdown, piping, ventilation, effects of grouting and of stray materials, the EDZ (principally an issue in clay and salt host rocks) and biological activity.

Consideration of 'pre-closure processes' and potential approaches to managing their effects suggests that, although they do need to be taken into account, they do not pose a significant obstacle to demonstrating acceptable levels of repository safety.

V.B. Processes Issues and Repository Design

A number of requirements, constraints and processes will influence the design of a repository and the EBS. In repositories for spent fuel and high-level wastes, heat from the waste will be the primary factor determining the temperatures that will develop. Repository temperature is an important constraint on repository design. In order to build confidence in the suitability of a repository design, it is necessary to conduct an iterative series of assessments of repository performance and disposal system safety. These assessments need to take account of repository evolution and this can be achieved by considering a range of scenarios. It is also essential that such assessments are based on a sufficient level of process understanding and associated data.

Studies aimed at refining and optimising the design of a repository need to consider a wide range of different types of information, including, results from feasibility, cost, performance and safety assessments for alternative repository and EBS designs. Repository design might be optimised in respect of heat production by adjusting waste canister spacing so that the waste inventory can be disposed of within acceptable temperature and safety limits, and the costs of repository excavation remain reasonable.

VI. MODELLING: ROLE IN THE SAFETY CASE

EBS Project Workshop 3 [8] focused on the role of modelling in supporting the safety case.

VI.A. Status of Available Models

The radioactive waste disposal community has developed, tested and applied many capable modelling tools, and although there may be some programme-specific gaps and more data may be required, the capability exists to model and assess most processes and process couplings. For example, capable two and three-dimensional modelling codes have been developed to simulate thermal, hydraulic, mechanical, and chemical (THMC) processes in repository systems and the couplings amongst them.

Such models can be beneficial in terms of developing and demonstrating understanding of disposal system behaviour (e.g., Fig. 2). However, limitations exist in the availability of data with which to parameterize coupled THMC models, particularly at elevated temperatures, and further limitations arise from the increased computational complexity and effort required to fully evaluate uncertainties in strongly coupled systems.

There are also potentially significant difficulties associated with the rigorous application and validation of some types of coupled process models over time and length scales relevant to disposal system safety assessment. As a result of these limitations and potential difficulties, pragmatic decisions have to be taken regarding the degree to which it is appropriate to directly incorporate detailed process-level modelling codes in safety analyses.

VI.B. Relationship between PA/SA Models and Process Models

To understand how PA/SA models and process models relate to each other, it is first appropriate to broadly define their roles in the safety case. Process models describe the potential behaviour of subsystems (by considering the processes controlling them) over a potentially large range of boundary conditions. One of the key messages to come out of process modelling is that the basic science is well understood and captured by the given process or research model. PA/SA models, on the other hand, evaluate the possible range of expected system behaviour (rather than subsystem behaviour) and, as such, often constrain the application of process models to a narrower range of behaviour. The PA/SA models may, thus, provide a coherent, system-wide set of conditions and parameter ranges. The key message to come out of PA/SA models is that the EBS works as designed and will fulfill its safety functions.

Information can be passed between PA/SA models and process models in both directions:

- Transferring fundamental safety relevant aspects or functions (physical-chemical processes, such as fluid flow and geochemistry) from process models to PA/SA models is known as the process of model abstraction. Transferring data, including process model outputs, to the spatial and temporal scale of the disposal system is known as upscaling.

- Transferring information from PA/SA models to process models can be useful in providing consistent boundary conditions to all process models. PA/SA models can also be used to put the results from process modelling studies into the wider context so that the significance of individual FEPs or combinations of FEPs can be understood.

Of course, the need to manage and record the transfer of such information is not only an issue for EBS modelling but also applies to geosphere modeling for example. However, it is principally in the context of considering the EBS, that such information transfer may affect repository design. It is, therefore, particularly important to ensure appropriate integration between EBS modeling at the PA/SA and process levels with design repository studies.

VI.B.1. Model Abstraction

Model abstraction, upscaling, the specification of boundary conditions, and the interpretation of PA/SA results cannot be fully automated because they require expert judgement, but there may be scope to develop more formal procedures or guidance on these topics in order to improve consistency of approach, transparency and QA.

It is tempting to assume that model abstraction involves a one-way process in which process models are simplified to develop PA/SA models. However, when developing a PA/SA model it can be necessary to take account of FEPs that do not need to be considered in process-modelling studies, such as the geometry and spatial heterogeneity of the disposal system. PA/SA modelling may also need to take account of a range of different types of data, such as that from natural analogue observations and information on the as-built repository. Experience from the more mature programmes that have gone through several cycles of PA/SA, suggests that the process of model abstraction involves iteration, a two-way flow of ideas and information, and that cycles of model development may result in oscillation over time between more and less elaborate models.

Approaches to model abstraction can also vary from the straightforward to the elaborate. It is sometimes straightforward to reduce complexity by making conservative assumptions, although demonstrating that an assumption remains conservative under all potentially reasonable circumstances may be difficult. It may also be possible to simplify by reducing the dimensionality of the analysis (e.g., by using one-dimensional or radial models). More elaborate approaches to abstraction might, for example, take advantage of the reduction in THMC gradients after the early post-closure period such that models for the far future need not consider all of the THMC interactions. The latter approach would also be consistent with the idea that it is more difficult to justify the use of elaborate models for the far future, given the generally increasing uncertainties with time.

VI.B.2. Upscaling

The need for upscaling is unavoidable and represents a source of uncertainty that needs to be accounted for in PA and SA. Examples of where the need for upscaling might be encountered include:

- Extrapolating from short-term experiments to repository timescales of thousands of years. Many chemical processes (e.g., gas generation, radionuclide desorption) tend to exhibit two characteristic rates – a relatively fast initial rate, which is relatively easily quantified in experiments, followed by a slower long-term rate, which may be more difficult to measure. Where it can be justified some programmes assume that although dis-equilibrium (kinetically controlled) processes are observed in the laboratory, these can be represented in PA/SA using equilibrium models based, for example, on modelling of long-term geologic processes represented by natural analogues.

- Extrapolating from short spatial scales (e.g., laboratory based radionuclide transport experiments using column tests) to the repository scale, taking account of spatial heterogeneity. Parameters that may be affected include hydraulic conductivity, diffusivities and sorption coefficients.

In more detail, several relatively complex areas of assessment were identified during Workshop 3 in which further dialogue amongst member states, particularly amongst the most experienced practitioners, might usefully be conducted with the aim of developing new or improved guidance on best practice and procedures that would serve to improve the conduct and traceability of modelling work supporting the safety case.

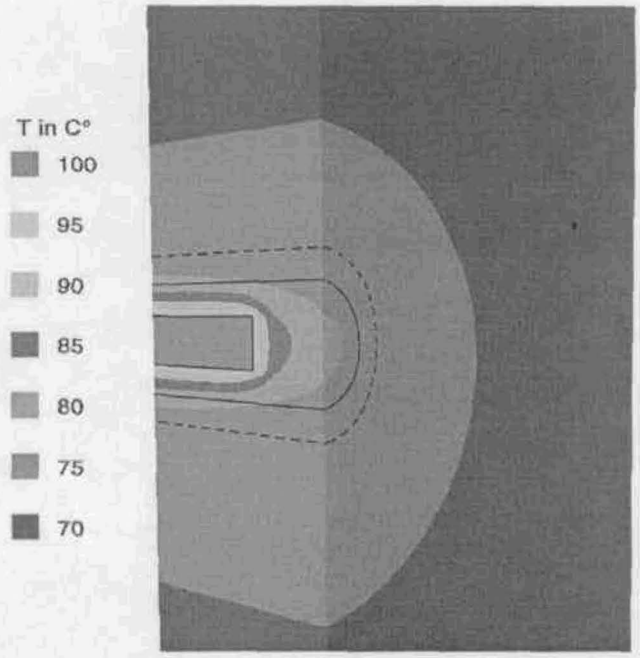

Fig. 2. Example modeling results obtained in support of development of thermal criteria for a Swiss SF/HLW repository in Opalinus Clay and showing the temperature distribution around disposed spent UO_2 fuel after a period of ~250 years after emplacement in the repository [9].

These areas include:

- Assessing and accounting for the probabilities of future events and processes in safety assessment and design optimisation / risk management.

- Model simplification / abstraction.

- The scaling of information and models to the scale of safety assessment.

- The treatment of spatial variability.

VII. RECENT TRENDS IN EBS STUDIES

Some national waste management programmes are placing increased emphasis on the EBS and, particularly as repository implementation is approached, there will be a need to make more realistic assessments of EBS performance, so that the design of the EBS and the costs of waste management and disposal can be optimised.

Optimisation should be approached on several levels, and programmes aimed at optimising the design of the disposal system and the EBS need to include SA, PA and process level modelling studies. SA and total system PA are best suited to informing choices over large scale issues, such as the choice of repository layout and the waste inventory. Subsystem PA models and process level models may be useful when considering smaller scale issues, such as the choice between alternative engineered barrier materials.

More emphasis is also being placed on the use of PA and SA models to integrate a wide range of information and help in communicating understanding of likely disposal system behaviour. Other ongoing and positive developments include:

- The establishment and use of Safety Function Indicators and Safety Functions for components of the EBS. In Sweden, SKB has developed a concept involving the use of defined Safety Function Indicators to provide a structured approach to linking between PA and EBS and repository design [10]. In Belgium, ONDRAF / NIRAS has identified a series of Safety Functions as a means to communicating how the disposal facility will achieve safety and to help in structuring the design process [11]. ONDRAF / NIRAS has recently adopted a revised EBS design for HLW disposal based on use of a Supercontainer [12].

- Moves towards Requirements Management Systems and 'living' PA/SA models that will provide a traceable record of developments over the lifetime of the waste management programme.

As these developments are progressed, there will be a need to undertake assessments in an increasingly rigorous manner, and to place greater emphasis on quality assurance and quality control of the assessment and implementation process.

VII. CONCLUSIONS

The NEA EBS Project is providing an on-going international forum for the exchange of ideas and information, and is promoting the development of best practice by developing structured methods for the design, characterisation, assessment and optimisation of engineered barriers and radioactive waste repositories and the associated safety cases.

Two project workshops, in particular, considered EBS process issues and the role of the modelling in the safety case:

- Workshop 2, Las Vegas, USA, 14-17 September 2004 [7].

- Workshop 3, La Coruna, Spain, 24-26 August 2005) [8].

These workshops allowed an assessment of the state-of-the-art in 2004/5 in considering such issues during safety case development.

Workshop 4 will complete the optimisation cycle (Fig. 1). It has a provisional title of 'Design Confirmation and Demonstration' and may consider:

- The application of quality assurance and quality control procedures to repository implementation and EBS fabrication, construction and emplacement.

- Programmatic activities that might form part of the post-licensing period during repository construction and operation, such as monitoring of the EBS and testing of models of EBS performance.

- The types of EBS design modifications that may require re-assessment.

- The performance and safety analyses that may be required to take account of the 'as-built' repository.

- Results from demonstration experiments and large scale tests of the EBS made under realistic repository conditions to assess the feasibility and problems of implementation.

It is expected that the Workshop 4 will be held in Japan during fall 2006.

It is also planned to reassess the state-of-the-art across all areas covered by the EBS project in 2006/7 and to develop an updated state-of-the-art report.

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